

# Dual Josephson Impedance Bridge: Universal bridge for impedance metrology

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**Abstract**—This paper describes the results of the calibration of a 100 pF capacitance standard performed at 1233 Hz. Two calibration chains were used. The classical calibration chain, involving a quadrature bridge and a 1:10 ratio bridge, and the faster and simpler calibration chain based on the Dual Josephson Impedance Bridge (DJIB). The results of the two procedures are in agreement within the uncertainty of the DJIB ( $u(k=1)=57 \text{ nF/F}$ ), which is slightly smaller than the uncertainty of the classical calibration chain presently in operation at METAS.

**Index Terms**—Capacitance calibration, impedance comparison, AC Josephson voltage standard, Josephson arbitrary waveform synthesizer, ac coaxial bridge.

## I. INTRODUCTION

Impedance metrology makes intensive use of ac coaxial bridges for the realization of the capacitance, resistance and inductance scales. The type and complexity of the bridge depends on the type of the comparison: ratio bridge for the comparison of impedances of the same kind, quadrature bridge for comparing capacitance to resistance, and Maxwell-Wien or resonance bridge for comparing inductance to resistance and capacitance (see [1] and references therein). A shared property of these Wheatstone-like measuring circuits is that, once the bridge is balanced, the impedance ratio to be measured is directly given by a voltage ratio. The precise and accurate generation or measurement of this voltage ratio is therefore the cornerstone of impedance metrology.

The unique quantum-based ability of Josephson Arbitrary Waveform Synthesizers (JAWS) to generate accurate and distortion-free voltage waveforms sparked the development of new impedance bridges where the voltage ratio is directly given by two synchronized JAWS systems. The potential of such Dual Josephson Impedance Bridges (DJIB) to compare any two impedance standards, regardless of type (R-C, R-L, or L-C) or ratio, over a large frequency range (from 1 kHz to 20 kHz) has been demonstrated [2]. Moreover, the direct comparison of a 10 nF capacitance standard to the quantum Hall resistance with a relative uncertainty smaller than  $1 \times 10^{-8}$  at 1233 Hz [3] has clearly shown the high accuracy potential of DJIB comparisons.

## II. BRIDGE DESCRIPTION

The DJIB has been designed to accurately determine the ratio of any two impedance standards defined as four-terminal

pair standards. The bridge is computer controlled, though the operator must still manually change the connections between the impedance standards and the bridge. The improved version used here is very similar to the earlier prototype described in [2]. The improvements are described in [4]; they mostly concern:

- An overall reduction of the cross-talk between various components of the system.
- An improvement of the galvanic separation between the bridge circuitry and the electronics of the auxiliary voltage sources and digitizers.
- An increase of the upper bridge frequency from 20 kHz to 80 kHz.

## III. CALIBRATION OF 100 PF CAPACITANCE STANDARD

As shown in Fig. 1, the classical calibration chain of a 100 pF standard performed at METAS [5] requires the use of two different ac coaxial bridges: First, a quadrature bridge is used to compare a pair of 12.906  $\Omega$  calculable resistors to a pair of 10 nF capacitors in a 1:1 ratio at the frequency of about 1233 Hz. Then a measurement with a 1:10 bridge is performed three times to step down the capacitance from 10 nF to 100 pF. Each 10 nF capacitor is compared to a single 1 nF standard, and finally, the 1 nF is compared to 100 pF standard.

The use of the DJIB greatly simplifies the calibration procedure because the same bridge can be used for both the R-C comparison and for the C-C comparisons. Moreover, the whole calibration chain can be reduced to a two-step comparison if the 12.906 k $\Omega$  resistor is directly compared to a 1 nF capacitor in a 1:10 R-C comparison.

Figure 2 shows the results of the calibration of a 100 pF standard performed over a period of almost 2 years. In 2017, the 100 pF standard was used for the METAS measurements in the CCEM-K4.2017 key comparison [5]. Therefore, the standard was calibrated at METAS, at the Bureau International des Poids et Mesures (BIPM), and back at METAS over a four month period. In December 2018, the 100 pF standard was calibrated again using both the classical and DJIB calibration chains.

The linear drift calculated from the classical calibrations performed at METAS is about 36 nF/F per year (see black line Fig. 2). The two other lines are parallel to the drift but

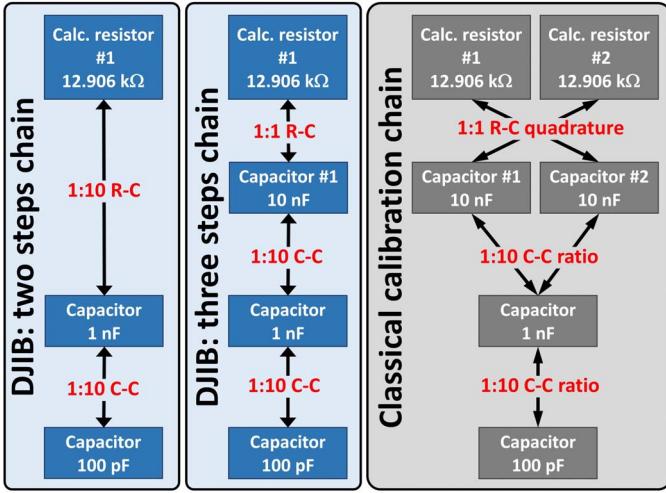


Fig. 1. Representation of different measurement chains leading to the calibration of 100 pF capacitance standard at 1233 Hz. The classical calibration chain requires two different bridges: a quadrature bridge and a 1:10 ratio bridge. Using the DJIB, the realization of the calibration chain is greatly simplified (see text for details).

shifted to fit the BIPM measurements (blue line) and the DJIB measurements (red line).

The uncertainty bars represent the combined standard uncertainty ( $k=1$ ) and are slightly smaller for the DJIB measurements (57 nF/F) than for the METAS classical calibration chain (68 nF/F). The DJIB and classical measurements are in agreement within the uncertainties (see Fig. 2 b). However, a small systematic offset (36 nF/F) can be observed between the DJIB and the classical calibrations. Although this offset is smaller than the uncertainty, it corrects approximately half of the systematic bias of the METAS classical calibration chain revealed during the CCEM-K4.2017 comparison [5].

It is worth noting that the classical calibration chain leads to the determination of the 100 pF value under a rms voltage of 10 V, while the DJIB comparisons are performed with a maximum rms voltage of 0.3 V. However, no voltage correction, estimated to be less than 3 nF/F per 10 V [6], has been applied.

Finally, the calibration of the 100 pF capacitor performed with the DJIB using the three step measurement gives the same result as the two step measurements (see Fig. 2 b).

#### IV. CONCLUSION

The results of the calibration of a 100 pF capacitance standard performed at 1233 Hz using the DJIB is simpler, faster and requires fewer measurement steps than the classical calibration chain in operation at METAS. The results of the two calibration chains are in good agreement. The uncertainty of the DJIB calibration chain (57 nF/F for  $k=1$ ) is slightly smaller than the uncertainty obtained at METAS with the classical calibration chain. As a result, METAS will employ the DJIB for realization of the capacitance scale and the quadrature bridge will be disassembled.

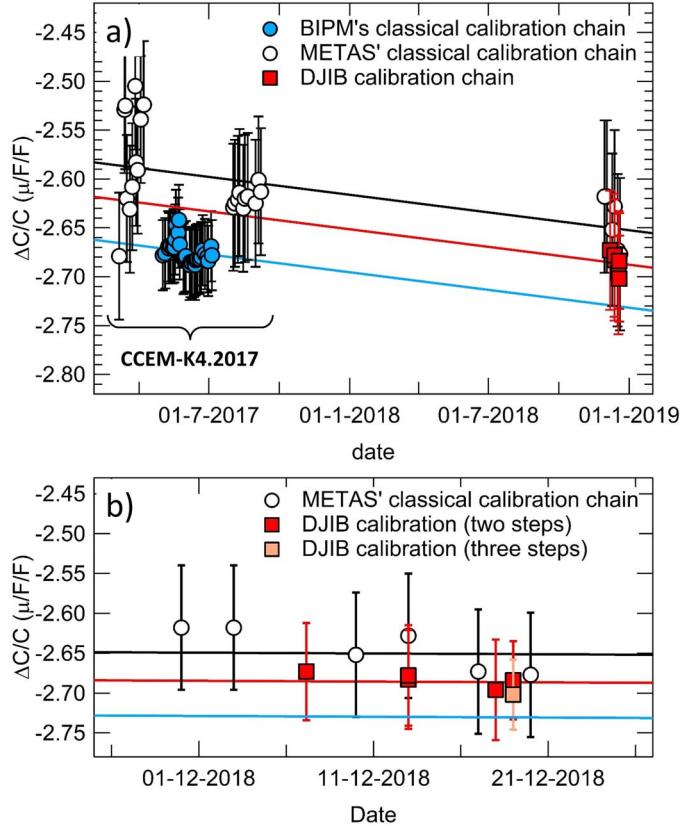


Fig. 2. Results of the calibration of a 100 pF capacitance standard versus time (day-month-year) performed using both a classical calibration chain at METAS and BIPM (circles) and using the DJIB, either in a two or three step measurement (squares). The three parallel lines are fits to the different data sets. The slope of the lines is determined using the classical calibration performed at METAS. a) Results over the whole period of almost 2 years. b) Closer view of the results obtained in December 2018. The uncertainty bars correspond to the combined standard uncertainty ( $k=1$ ).

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